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Extended Composite Table Algorithm for Optimal Planning of Unconventional Gas Field Development

Reza Parand[a,*], Dominic C.Y. Foo[b], Raymond E.H. Ooi[b], Raymond R. Tan[c], Jui-Yuan Lee[d]

[a]School of Built Environment, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
[b]Department of Chemical & Environmental Engineering/Centre of Excellence for Green Technologies, University of Nottingham, 43500 Semenyih, Selangor,Malaysia
[c]Chemical Engineering Department/Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines
[d]Department of Chemical Engineering and Biotechnology, National Taipei University of Technology, 1, Sec. 3, Zhongxiao E. Rd., Taipei 10608, Taiwan, R.O.C.
rezaparand@gmail.com

Lately, there has been an increase in utilization of natural gas, as a relatively clean fossil fuel in place of coal as we move towards the use of low-carbon energy sources. As a result, there is a need to recover natural gas from high concentration carbon dioxide (CO_2) gas fields which have been regarded as uneconomical to be developed previously. In such cases, naturally occurring CO_2 needs to be separated from natural gas or reduced to a lower content to meet sales gas specifications and utilization for power generation. Meanwhile, the separated CO_2 needs to be disposed or utilized efficiently for consumption by various processes. In this work, we develop a variant of the composite table algorithm to be applied in the planning of field development involving high CO_2 gas field, often considered as unconventional resources. This methodology is superior to previously developed graphical approach as the model is able to solve more generic cases without imposing strict assumptions on stream purity requirements. The methodology is illustrated using case studies such as those demonstrated in the paper.

1. Introduction

It is well understood that human activities place significant stress on natural ecological systems. As such, climate change is widely regarded as the single most important environmental issue affecting the world today (Steffen et al., 2015). Despite the continuously increasing share of renewable energy sources (e.g. solar, wind, etc.) in today's modern world, fossil fuels remain as the primary energy source although it has long been identified as a major contributor to the worsening greenhouse effect. Among various fossil fuels, natural gas (NG) is considered a relatively clean energy source with lower CO_2 intensity (as compared with oil and coal).
The sweetening of sour NG is essential for some reasons. Firstly, the presence of CO_2 reduces the heating value of NG. In addition, CO_2 may clog and damage pipes and equipment because it is corrosive and potentially forms hydrate at low temperatures. For offshore facilities, CO_2 from NG is typically captured in-situ before it is being sent to the gas processing plant (GPP) onshore. Removal of CO_2 offshore offers many advantages such as reduction in export gas compression duty (e.g. less gas flowrate once CO_2 is removed) and selection of conventional pipeline materials (e.g. non corrosion resistant). The captured CO_2 can be utilized to support enhanced oil recovery (EOR) operations or sent for permanent storage in depleted reservoirs (CO_2 sequestration). The sweetening units are required to reduce the content of CO_2 in NG to the level acceptable for the GPP. The blending of sour gas with sweet gas (SG) with lower CO_2 content to meet the required specification of sales gas is a common practice in the industry, in order to reduce dependency on gas sweeting units, or to optimize the units with lower design capacities to meet affordability. However, SG normally has limited availability. Therefore, achieving optimum utilisation of SG is desired.

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Within the community of Process Integration, several techniques have been developed for removing a specific impurity in process streams. In the seminal work of mass exchange network (MEN) synthesis (El-Halwagi and Manousiouthakis, 1989), the graphical Pinch Analysis was developed to identify the minimum mass separating agent required to remove specified loads from impurity-rich streams. Based on MEN design, Wang and Smith (1994) developed a graphical Pinch Analysis method for water network design. This technique is, however, limited to fixed-load problems and the flowrate losses within processes cannot be considered. Several water Pinch Analysis techniques – such as Water Cascade Analysis (Manan et al, 2004), Material Recovery Pinch diagram (El-Halwagi et al, 2003), Water Source Diagram (Bandyopadhyay, 2006), and Composite Table Algorithm - CTA (Agrawal and Shenoy, 2007) – have been developed later to deal with fixed flowrate problems, where the outlet flowrate of a process unit can be different from its inlet flowrate. Among these methods, CTA appears to be advantageous because it is similar to the Limiting Composite Curve method of Wang and Smith (1994), and is a hybrid of graphical and numerical approaches. In Parand et al. (2014), the Composite Matrix Analysis was developed within CTA for water regeneration-reuse networks. Parand et al. (2016a) later extended the CTA as automated Composite Table Algorithm (ACTA) approach for zero liquid discharge networks. In Parand et al. (2016b), ACTA has been adopted in water regeneration-recycling networks. Note however that, these earlier works focused on water recovery rather than waste treatment, where the gas sweetening problem is analogous to. One of the developed method for wastewater treatment targeting was reported by Ng et al., (2007), who developed the Wastewater Treatment Composite Curve for targeting the minimum impurity load removal, for both fixed outlet concentration and removal ratio types waste treatment units. Soo et al. (2013) later extended the work for a single and two contaminant systems with multiple treatment units. These waste treatment targeting works form the basis for the work by Foo et al. (2016), who proposed a graphical technique to identify the minimum extent of CO_2 removal for the NG sweetening problem.

In this work, CTA is extended to solve the sour NG sweetening problem in unconventional gas field development. The CTA overcomes the limitation of the graphical technique proposed by Foo et al. (2016) which requires that the CO_2 content of SG being the same as that of the purified stream of the gas sweetening unit. The rest of the article is organized as follows. A formal problem statement is given in the next section, followed by the description of the developed methodology. Next, a literature example is presented to elucidate the developed methodology through two different cases. Finally, concluding remarks are made.

2. Problem statement

The formal problem to be addressed is stated as follows. Given:

- A set of sour NG sources where CO_2 is to be removed before gas streams are sent to the downstream GPP. The latter can tolerate a certain maximum of CO_2 content at plant inlet onshore.
- A set of gas sweetening units of known performance (i.e. outlet CO_2 concentration). The flowrate and CO_2 load balances of such a unit are given in Eqs(1) and Eq(2).

$$F_{Rin} = F_{RP} + F_{RJ} \tag{1}$$

$$F_{Rin}C_{Rin} = F_{RP}C_{RP} + F_{RJ}C_{RJ} \tag{2}$$

where F_{Rin}, F_{RP}, and F_{RJ} are flowrates of the inlet, purified, and reject streams, while C_{Rin}, C_{RP}, and C_{RJ} are their respective CO_2 concentrations. The product recovery factor given in Eq. (3) is one of the important characteristics of a gas sweetening unit.

$$RC = \frac{F_{RP}(100 - C_{RP})}{F_{Rin}(100 - C_{Rin})} \tag{3}$$

- Two types of gas sweetening units (namely amine absorption and membrane) are typically adopted for offshore gas processing. The capital and operating costs of such units depend on the amount or extent of CO_2 removal required to meet the sale gas specification of the GPP onshore.
- The decision for the amount of CO_2 removal from sour gas is made by considering the trade-off between the capital/operating cost of gas sweetening units and adopting gas blending with lower CO_2 content from other sources.
- Scarcity of low-CO_2 SG supply in today's remaining gas reserves due to extensive exploration and development of conventional gas fields over the years.
- Note that the total flowrate of NG sent to the GPP is lower than the original flowrate from the gas fields source due to flowrate losses in gas sweetening units (Eq. 3). Since the total flowrate requirement upon arrival at GPP is fixed and determined by demand/ users, the flowrate reduction needs to be supplemented and this can be done by introducing low-CO_2 SG either from a new gas field yet to be developed or an existing operational gas field.

- The reject stream are usually sent to depleted reservoirs for permanent storage (CO_2 sequestration) or injected into oil producing reservoirs to support EOR operations.

The main objective of the problem is to determine the minimum extent of CO_2 to be captured from sour gas, while achieving the minimum sweet gas supplement. Since SG normally has limited availability, it is important to minimize its usage.

3. Extended CTA

CTA was originally developed for targeting fixed flowrate problems in water network synthesis (Agrawal and Shenoy, 2007). It is later improved by (Parand et al. 2016b) for water regeneration system to address RR type regeneration units and consider economic optimization in targeting stage. In this study, CTA will be extended to account for flowrate losses in purification unit. We consider its application for optimal planning of gas field development.

In the seminal work of Foo et al. (2016), new process integration graphical technique was developed with the aim of planning the development of contaminated gas fields (offshore) together with conventional sweet gas field (onshore) to achieve the required sales gas specification of CO_2 content. However, the proposed graphical methodology has a major drawback i.e. the CO_2 concentration of the sweet gas is assumed to be equal to that of purified stream of the gas sweetening unit. This requirement imposed on the quality of SG which can be used to make-up or supplement flowrate losses and provide gas blending limits the source of SG fields which can be paired with the network to provide an integrated field development plan. Hence the extended CTA in this study addresses the shortages of the method proposed by Foo et al. (2016).

The procedure for extended CTA is given in Figure 1 and detailed description is as follows.

3.1 Step 1 – The implementation of CTA

The CTA as developed by Agrawal and Shenoy (2006) is constructed. The procedure is described below

- Identify CO_2 concentration levels (C_k): Arrange CO_2 concentration including the largest arbitrary value in increasing order. Note that the concentration of purified stream (C_{RP}) should be included.
- Identify the interval net flowrate (Net F_k): For each concentration interval, the sum of flow rates of process sources (SG fields) is subtracted from the sum of flow rates of process sinks (GPP).
- Determine the interval impurity load (Δmk) These values are calculated by multiplying the interval net flow rate with the difference of contaminant concentration levels.
- Calculate the cumulative load (Cum Δmk): By assuming the zero impurity load as the first entry, the interval impurity load is cascaded down to generate the cumulative load.
- Deduce the interval inlet flowrates ($F_{Rin,k}$) without considering the reject stream via Eq(4).

$$F_{Rin,k} = \frac{Cum\ \Delta m_k}{C_k - C_{RP}} \qquad (4)$$

3.2 Step 2 – Identify Inlet concertation (C_{Rin})

Inlet concentration is readily determined by using a simple mass balance around the sour gas fields Eq(5). Where $F_{Fpi,Api}$ is the flowrate allocation of the pinch source to the above pinch region and C_{pi} is the pinch concentration.

$$F_{Fpi,Api} C_{pi} + \sum_i F_i\, C_i = F_{Rin} C_{Rin} \qquad (5)$$

3.3 Step 3 – Identify purified flowrate (F_{RP})

RC is the product recovery factor and a given value, thus F_{RP} is now calculated by using Eq(3) provided earlier.

3.4 Step 4 – Re-implementation of CTA to identify flowrate of sweet gas (F_{SG})

The CTA is reconstructed (as described in Step 1) by including purified stream (F_{RP}, C_{RP}) as one of the sources. Please note that the C_{RP} is a given value. The optimum flowrate of sweet gas (F_{SG}) is the largest among the $F_{Rin,k}$ entries. The CO_2 concertation as the F_{SG} level is also a pinch point.

3.5 Step 5 – Re-calculation of inlet flowrate

F_{Rin} is recalculated by two simple flowrate balances. First, the flowrate balance is conducted around the GPP as Eq(6).

$$F_{GPP} = F_{SG} + F_{RP} + F_{Fpi,Bpi} \qquad (6)$$

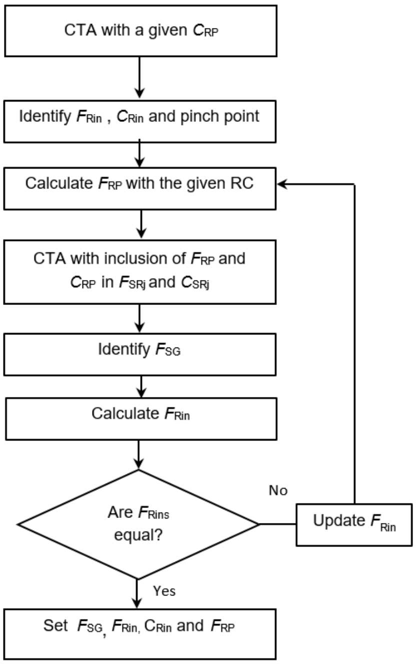

Figure 1: Extended CTA procedure

where F_{GPP} is the given gas processing plant flowrate. F_{SG} and F_{RP} have been determined in earlier steps. $F_{Fpi,Bpi}$ is the flowrate allocation of the pinch source to the below pinch region which is unknown and can determined. Note that Pinch source was identified in the previous step.
Second, the flowrate balance is constructed around sour gas sources Eq(7).

$$F_{Rin} = \sum_i F_i + F_{Fpi,Api} \tag{7}$$

where $F_{Fpi,Api}$ is the flowrate allocation of the pinch source to the above Pinch region. $F_{Fpi,Api}$ is readily calculated since the total flowrate of Pinch source is a given value. Now, F_{Rin} is re-calculated.
If the later F_{Rin} is identical to the former value which was identified in step 1 of the procedure explained above, all the targeting values are known and iteration is complete. Otherwise, the procedure considers the later F_{Rin} and recalculates F_{RP} and iteration continues until the convergence criteria (i.e. equal F_{Rin}s) is satisfied. The applicability of this procedure is demonstrated through a literature example in the next section.

4. Illustrative example

In this section, a literature example is solved to illustrate on the proposed approach Table 1 shows the data for gas sweetening case study taken from Foo et al. (2016). A total of three gas fields each with significant CO_2 content are to be developed. The CO_2 content has to be reduced to 3 % or lower before the gas can be sent to the GPP. It is desired to minimise the flowrate of SG, in this scenario to be supplied from Field D. Also, it is assumed that the total flowrate to GPP is kept at 10^6 m^3/h as per its design capacity. Two different cases are considered in this study.

Table 1: Data for gas sweetening case study

	Flowrate, F_i (Sm^3/h)	CO_2 content, C_i	CO_2 load, m_i (m^3/h)
Field A	500,000	15%	75,000
Field B	300,000	30%	90,000
Field C	200,000	50%	100,000
Field D (Sweet gas)	TBD	2%	TBD

4.1 Case 1: C_{RP} = C_{SG} = 2 % & RC = 95 %

A purification unit is assumed to have an outlet concentration (C_{RP}) of 2 % and an RC of 95 %. A SG source with 2 % CO_2 content is available to supplement the flowrate losses due to gas sweetening. The first step is to construct the CTA as shown in Table 2.

Table 2: Implementation of CTA

k	C_k(%)	GPP 1,000 (x 10^3 m^3/h)	Field A 500 (x 10^3 m^3/h)	Field B 300 (x 10^3 m^3/h)	Field C 200 (x 10^3 m^3/h)	Net F_k (x 10^3 m^3/h)	Δm_k (x 10^3 m^3/h)	Cum.Δm_k (x 10^3 m^3/h)	$F_{Rin,k}$ (x 10^3 m^3/h)
1	C_{RP}=2							0	0
						0	0		
2	C_{GPP}=3							0	0
						1,000	12,000		
3	C_{pi}=15							12,000	F_{Rin}=923.1
						500	7,500		
4	30							19,500	694.4
						200	4,000		
5	50							23,500	489.6
						0	0		
6	60							23,500	405.17

Both the concentrations of the GPP and the purification unit are considered in the list of concentration levels. The F_{Rin} is identified as 923,100 m^3/h and the Pinch concentration is 15 %. Next the inlet CO_2 concentration to the gas sweetening unit is identified using Eq(5), i.e. 500 × 15 + 300 × 30 + 200 × 50 = 923.1 × C_{Rin}. The CO_2 concentration is determined as 27.5 %. In step 3, F_{RP} is calculated as 648,800 m^3/h via Eq(3). For step 4, the CTA is reconstructed by including the purified stream (C_{RP}= 2% & F_{RP} = 648.8 MMscfd) as one of the sources. The flowrate of sweet gas (F_{SG}) is identified as 274,300 m^3/h (the largest value among the $F_{Rin,k}$ entries) and the Pinch concentration is 15 %. The implementation of CTA is not included for this step for brevity. Next, F_{Rin} is recalculated via Eq(6) and Eq(7). Through the former equation $F_{pi,Bpi}$ is identified as 76,900 m^3/h and the latter equation identifies F_{Rin} as 923,100 MMscfd. Since this F_{Rin} is identical to the one identified earlier in step 1, all targeted values are determined and further iteration is not needed. These values completely agree with those reported by Foo et al. (2016). The network structure for gas sweetening system is depicted in Figure 2(a). In this case, the sweet gas has the same CO_2 concertation as the purified stream of the gas sweetening unit which is the main limitation of graphical method in Foo et al. (2016). In the next case, a similar example is considered but different CO_2 content is assumed for SG and the purified stream.

4.2 Case 2: C_{RP} = 2 %, C_{SG} = 1 % & RC = 95 %

For Case 2, the CO_2 concentrations of the purified stream and the sweet gas are assumed to be 2 % and 1 %, respectively. In Step 1, the CTA identifies the inlet gas sweetening flowrate (F_{Rin}) of 923,100 m^3/h. Next the inlet concertation is also determined as 27.5 %. The purified flowrate is calculated as 649,000 m^3/h. In Step 4, the SG flowrate is determined to be 254,500 m^3/h. Next the inlet flowrate (F_{Rin}) is recalculated as 903,500 m^3/h. Since the later F_{Rin} is not equal to the earlier one identified in Step 1, the procedure goes back to Step 2 to recalculate the C_{Rin} and continues further for recalculation of other parameters. After 4 iterations, the convergence criteria is satisfied. The sweet gas flowrare, inlet flowrate, purified flowrate and inlet concentration are determined as 270,000 m^3/h, 902,400 m^3/h, 632,400 m^3/h, and 27.7 %. The network structure for gas sweetening system is depicted in Figure 2(b).

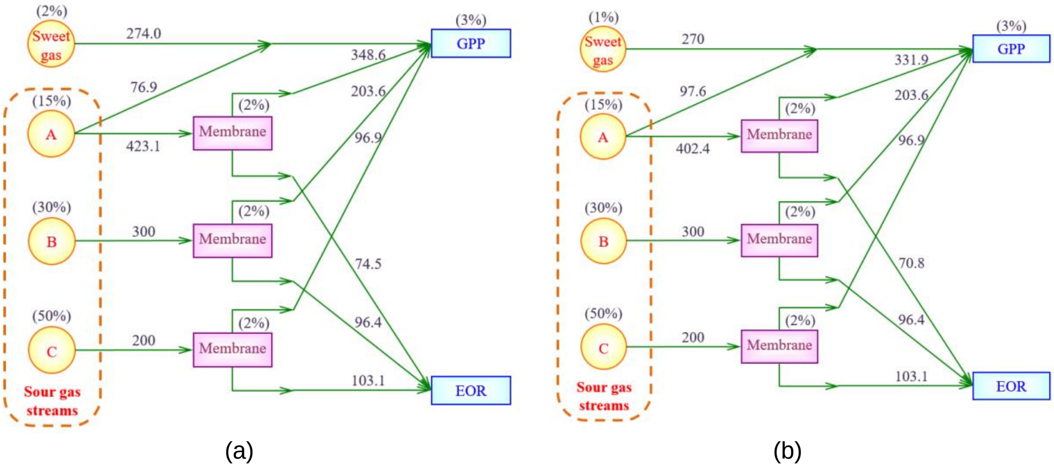

Figure 2: Network structure for gas sweetening system: (a) case 1 (b) case 2

5. Conclusions

In this paper, an extended composite table algorithm has been developed for the application of planning optimal development of unconventional gas fields. The new algorithm based on CTA overcomes the limitation of the earlier graphical technique, where the purified stream of the gas sweetening unit is limited to be the same CO_2 content as the SG. Besides, the CTA is algebraic in nature, which overcomes the tediousness and inaccuracy problem of the graphical approach. Future work may consider the use of gas sweetening units of different performance.

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